3:55 OCA PAD INITIATION - PROJECT HEADER INFORMATION 08/11/89

Active

ect #: E-25-M93 Cost share #: Rev #: 0
er # : 10/24-6-R6785-0A0 Center shr #: OCA file #:
Work type : RES
ract#: SS89-1956 Mod #: Document : PO
e #: Contract entity: GTRC

rojects ? : Y
project #:

ect unit: ME Unit code: 02.010.126
ect director(s):
KAHN B ME (404)894-3776

sor/division names: SOUTHERN COMPANY SERVICES /
sor/division codes: 218 / 025

d period: 890801 to 900131 (performance) 900131 (reports)

sor amount	New this change	Total to date
Contract value	14,804.00	14,804.00
Funded	14,804.00	14,804.00
sharing amount		0.00

subcontracting plan apply ?: N

e: POTENTIAL FOR IMPROVEMENT OF DOWNHOLE GAMMA-RAY LOGGING

PROJECT ADMINISTRATION DATA

contact: William F. Brown 894-4820

nsor technical contact	Sponsor issuing office
PATEL	JOHN BLAND
5)877-7697	(205)870-6928
THERN COMPANY SERVICES, INC.	SOUTHERN COMPANY SERVICES, INC.
. BOX 2625	P.O. BOX 2625
MINGHAM, AL 35202	BIRMINGHAM, AL 35202

rity class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
nse priority rating : NA NA supplemental sheet
pment title vests with: Sponsor GIT
NE PROPOSED

nistrative comments -
ITIATION OF E-25-M93. FINAL PMT. OF $3,000 WILL BE WITHHELD BY SPONSOR
TIL ACCEPTANCE OF A FINAL REPORT IS RECEIVED.

3:56	SUBPROJECTS OF MAIN PROJECT E-25-M93		08/11/89
ect number	Spon/Div	Project Director	Project Unit
		Total Contract	Total Funded
5-633	218/025	WAMPLER J M	GEO SCI
		11,725.00	11,725.00

0:24 OCA PAD INITIATION - PROJECT HEADER INFORMATION 08/11/89

SUB UNDER E-25-M93

Active

ect #: G-35-633 Cost share #: Rev #: 0
er # : 10/24-6-R6785-0A1 Center shr #: OCA file #:
Work type : RES
ract#: SS89-1956 Mod #: Document : PO
e #: Contract entity: GTRC

rojects ? : N
project #: E-25-M93

ect unit: GEO SCI Unit code: 02.010.140
ect director(s):
WAMPLER J M GEO SCI (404)894-3893

sor/division names: SOUTHERN COMPANY SERVICES /
sor/division codes: 218 / 025

d period: 890801 to 900131 (performance) 900131 (reports)

sor amount	New this change	Total to date
Contract value	11,725.00	11,725.00
Funded	11,725.00	11,725.00
sharing amount		0.00

subcontracting plan apply ?: N

e: POTENTIAL FOR IMPROVEMENT OF DOWNHOLE GAMMA-RAY LOGGING

PROJECT ADMINISTRATION DATA

contact: William F. Brown 894-4820

nsor technical contact

PATEL
5)877-7697
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Sponsor issuing office

JOHN BLAND
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SOUTHERN COMPANY SERVICES, INC.
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BIRMINGHAM, AL 35202

rity class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
nse priority rating : NA NA supplemental sheet
pment title vests with: Sponsor GIT
NE PROPOSED

nistrative comments -
ITIATION OF SUBPROJECT G-35-633 UNDER MAIN PROJECT E-25-M93/KAHN/ME.

OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 07/18/90

: No. E-25-M93 Center No. 10/24-6-R6785-0A0

: Director KAHN B School/Lab MECH ENGR

: SOUTHERN COMPANY SERVICES/

:t/Grant No. SS89-1956 Contract Entity GTRC

Contract No.

POTENTIAL FOR IMPROVEMENT OF DOWNHOLE GAMMA-RAY LOGGING

ive Completion Date 900701 (Performance) 900701 (Reports)

it Actions Required:	Y/N	Date Submitted
ial Invoice or Copy of Final Invoice	Y	
ial Report of Inventions and/or Subcontracts	N	
vernment Property Inventory & Related Certificate	N	
assified Material Certificate	N	
lease and Assignment	N	
her	N	

iments

ject Under Main Project No.

ues Project No.

bution Required:

oject Director	Y
ministrative Network Representative	Y
RI Accounting/Grants and Contracts	Y
ocurement/Supply Services	Y
search Property Managment	Y
search Security Services	N
ports Coordinator (OCA)	Y
RC	Y
oject File	Y
her	N
	N

OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT (SUBPROJECTS)

Closeout Notice Date 07/18/90

: No. E-25-M93 Center No. 10/24-6-R6785-0A0_

: Director KAHN B_______________ School/Lab MECH ENGR______

: SOUTHERN COMPANY SERVICES/______________________________

: # G-35-633 PD WAMPLER J M Unit 02.010.140 T
SS89-1956 MOD# ADMIN. E & A SCI *
10/24-6-R6785-0A1 Main proj # E-25-M93 OCA CO WFB
:-SOUTHERN COMPANY SER / 218/025
IAL FOR IMPROV
390801 End 900701 Funded 11,725.00 Contract 11,725.00

ndicates the project is a subproject.
ndicates the project is active and being updated.
ndicates the project is currently active.
ndicates the project has been terminated.
ndicates a terminated project that is being modified.

POTENTIAL FOR IMPROVEMENT OF DOWNHOLE GAMMA-RAY LOGGING

First Bi-Monthly Progress Report

to

Southern Company Services, Inc.
P. O. Box 2625
Birmingham, Alabama 35202

October 6, 1989

Project No. E-25-M93

Bernd Kahn and J. M. Wampler, Principal Investigators

Georgia Institute of Technology
Atlanta, Georgia 30332

In order to identify state-of-the-art gamma-ray spectral logging techniques and neutron activation or other activation techniques that may be useful for the purposes identified by the sponsor, we have begun a systematic search of recently published technical literature on well-logging techniques and applications and have begun to obtain information about commercially available logging equipment from the manufacturers. The search of the literature, which is the primary responsibility of graduate research assistant Huizhen Gao, employs two different search methods: 1) a search for relevant books and articles listed in databases available through the Georgia Tech Electronic Library, and 2) manual searching of recent issues of periodicals that we have identified as the most important carriers of information about new developments in well-logging. Ms. Anna Butler has taken primary responsibility for solicitation of information from manufacturers of well-logging equipment, and she has made available her personal library of well-logging literature to supplement the literature available in the Georgia Tech Library.

The Georgia Tech Library has acquired a number of recently published books on well-logging and has current subscriptions to all of the more important journals that have articles on well-logging techniques. Two important new journals appear to be particularly important, and so we will be manually searching all issues of these journals for articles that may be relevant to the goals of this project. <u>Nuclear Geophysics</u> (Part E of <u>Int. J.</u>

radiat. appl. instrum.) began publication in 1987 and has articles about a variety of applications of nuclear techniques, both within and without the petroleum industry. SPE Formation Evaluation began publication in 1985 and has many articles on current techniques used in well logging in the petroleum industry. The petroleum industry has provided the major economic incentive for the development of downhole measurement techniques, so new developments in that industry may often be relevant to the work of this project.

By using databases available in the Georgia Tech Electronic Library, we have developed an ability to search large databases for articles and other publications of interest using keywords. Ms. Gao has searched several databases, in particular the Applied Science & Technology Index (ASTI), The Engineering Index (ENGI), INSPEC (INSP), and the Trade & Industry Index (TRND), for recently published articles that would be important for this project. She is developing a good understanding of the combinations of keywords that are most profitable in such a search, so that when we turn to databases such as GEO-REF, for use of which a fee will be charged, the cost of searching can be kept rather low. Included as an addendum to this report is a listing of a bibliography that Ms. Gao has prepared from her search of the databases listed above. She has prepared this bibliography by personally reviewing the citations obtained in the keyword searches and deleting articles that would be of no use for the purposes of this project.

We are fortunate to have the assistance of Anna Butler for the project. Ms. Butler has considerable experience as a professional well-log analyst in the petroleum industry, and she has maintained her interest in the field through current subscriptions to trade journals. She is compiling brochures and other literature from manufacturers of logging equipment and is helping us identify other important sources of information. We are in the process of obtaining the Proceedings of the Second International Symposium on Borehole Geophysics for Minerals, Geotechnical, and Ground Water Applications, which she has suggested as a particularly important source of information for this project. She has also learned that a third symposium on this topic was held recently, and she will help us obtain whatever information may be available about the proceedings of this most recent symposium.

We expect that the process of obtaining relevant literature and information from manufacturers will be essentially complete a few weeks hence. The process of evaluation of the information in the books, articles, and brochures, in order to judge how logging techniques might be used in or modified for use in the applications identified as important to the sponsor, is just beginning. We should be well into the process of evaluation by the end of October, at which time virtually all of the available literature should be on hand.

POTENTIAL FOR IMPROVEMENT OF DOWNHOLE GAMMA-RAY LOGGING

Second Bi-Monthly Progress Report

to

Southern Company Services, Inc.
P.O. Box 2625
Birmingham, Alabama 35202

December 22, 1989

Project No. E-25-M93

Bernd Kahn and J. M. Wampler, Principal Investigators

Georgia Institute of Technology
Atlanta, Georgia 30332

INTRODUCTION

The following pages comprise an annotated bibliography of recent papers the technical literature that we have identified as the most important to evaluation of the potential for improvement of downhole gamma ray logging. bibliography represents the status of our work on the project essentially f the end of November 1989.

Because of an illness that began just as the fall academic quarter was ng, the investigator [JMW] who had accepted the responsibility to compile annotated bibliography was unable to complete this report at the time ned. Consequently, the report is being submitted some two weeks later originally anticipated, the annotations are not as thorough as they might been, and the format of the bibliography is not as refined as we had d. We have not yet been able to include in the comments some of the ific items of information that have been requested, such as notes on the anies that provide the equipment and services.

In a final project report that we will be preparing in the near future, ill resubmit the annotated bibliography in a laser-printed format with nded comments that address particularly the importance of each paper in context of the goals of this research project. Some additional papers we have found to be important will be included in the final bibliography. ill include the information that we have been able to obtain on the lablity of equipment and services. Most important, we will include our uation of the potential of nuclear logging techniques for the particular ications that are of interest to the sponsor, with particular attention to measurement of the chemical elements that have been indicated by the sor to be of special interest.

Potential for Improvement of Downhole Gamma-Ray Logging

An Annotated Bibliography

ORGANIZATION OF CONTENTS

E-25-M93

POTENTIAL FOR IMPROVEMENT OF DOWN-HOLE GAMMA-RAY LOGGING

Final Report

to

Southern Company Services, Inc.

P.O. Box 2625

Birmingham, Alabama 35202

March 30, 1990

Project No. E-25-M93

Bernd Kahn and J. M. Wampler, Principal Investigators

Georgia Institute of Technology

Atlanta, Georgia 30332

1. INTRODUCTION

In the task of compiling information on gamma-ray logging techniques that are pplicable to the research interests of the sponsor, we are fortunate to have a relatively ecent monograph by A. W. Wylie (1984) that provides an excellent introduction to the arious nuclear techniques that have been used for quantitative measurement of radio-ctivity and elemental abundances in subsurface rocks by instruments that may be owered in boreholes. The book also provides a well-written and well-illustrated introduc-on to the nuclear physical principles on which these techniques are based, as well as brief introduction to the geochemistry of the naturally occuring gamma emitters.

In our review of the literature we have focused primarily on articles that have ppeared since 1984, when Wylie's book was published. We have used several atabases available in the "Georgia Tech Electronic Library" in a search for relevant rticles and books published during the last several years. These databases include ublications in the areas of engineering and mainstream physical science, but they are ot thorough in their coverage of geological literature. Therefore we have also con-ucted a search of the GEOREF database in order to find papers on geological pplications of the nuclear techniques that have been published during the past ten ears. We should also note that the period since publication of Wylie's book includes ıe advent of the journal *Nuclear Geophysics*, which is an excellent source of informa-on about current techniques for subsurface nuclear measurements. The *IEEE Transac-ons on Nuclear Science* has proved to be of comparable value as a source of recent rticles on nuclear well-logging techniques.

In our compilation of information we have found it necessary to go beyond the rea referred to in the original research objectives as "gamma-ray spectral logging," ecause there are other techniques that may be required to obtain information neces-ary for accurate calibration of the gamma-ray spectral techniques and because there re some cases among the elements (and radionuclides) that are of interest to the ponsor where other techniques are necessary in order to detect the species of interest. ı the following summary of logging techniques, therefore, some other techniques are ıcluded to complement the gamma-ray spectral techniques.

This report comprises a summary of the well-logging methods that may be useful) the sponsor, a description of the availability and cost of equipment and services for amma-ray spectral logging (particularly in respect to tools that employ high-resolution etectors), and recommendations for future work. Section 5 is a list of references cited i the body of the report.

The final section of the report is an annotated bibliography of recent publications iat we consider to be of particular importance to the sponsor. These publications iclude discussions of instruments for nuclear well logging (types of sources and etectors, optimum applications in terms of logging (travel) rates and geometric relaons between radioactive sources and detectors, newly developed instruments); use of ther information (density, porosity, rock constituents) in the analysis of data; algorithms or data analysis; and applications of nuclear data (attenuation factors, gamma-ray nergies, neutron cross sections, half-lives, etc.) in quantitative analysis by gamma-ray pectral measurements. The publications are arranged in a topical order according to ie following list of topics and sub-topics:

- Instrumentation
  - Nuclear logging tools
  - Electronics and components
  - Improvements and modifications
- Interpretation
  - Inversion of nuclear spectral data
  - Algorithms and models
  - Calibration
- Applications
  - Elemental analysis
  - Mineralogical composition and physical properties of rock
  - Character of subsurface fluids
  - Recent developments
- Reviews
- Books

ome of the papers in the bibliography could well fit under several of the topics in the st above. In each such case we have chosen to list the article under the topic that eems to be most appropriate, based on the overall content of the paper.

We have included in the annotated bibliography the published abstract for each aper that has such an abstract, and for nearly all of the papers we have added omments written either by J. M. Wampler or by Graduate Research Assistant Huizhen iao. (Ms. Gao's comments have been edited by J. M. Wampler in respect to usage of nglish but not generally in respect to content.) Initials are used to identify the author of ach set of comments.

Additionally we will provide for the sponsor (under separate cover) copies of those rticles in the annotated bibliography (and others in the list of references cited) which e may so provide without infringement of the copyright of the publisher. Such articles re those that are not subject to copyright in the United States, other articles for which ompensation to the publisher may be made through the Copyright Clearance Center, nd articles in published conference proceedings that we have purchased. Along with ese papers, we will send an alphabetical listing of all of the papers we have found in ur search of the well-logging literature that are, in our judgement, possibly relevant to e interests of the sponsor.

2. SUMMARY OF LOGGING METHODS

.1. Nuclear Logging Methods that Provide Direct Measures of Elemental Abundance

.1.1. Natural gamma-ray logging (and detection of artificial gamma emitters)

.1.1.1. High-energy gamma-ray spectrometry

Tools for measurement of natural gamma-ray activity normally employ NaI(Tl) cintillation detectors since these have greater sensitivity than the higher-resolution ermanium detectors and since the spectral resolution of the scintillation detectors is dequate to resolve radiation from the three major long-lived radionuclides (actually om short-lived daughters, in the cases of uranium and thorium). Scintillation detectors ıay also be useful for detection of certain artificial radionuclides in the subsurface nvironment.

The higher resolution of germanium detectors is required in order to measure ranium when there is not equilibrium throughout the decay series (Tanner, 1982). Such etectors may also be necessary to distinguish certain artificial radionuclides in the ubsurface. Although the efficiency of such detectors is considerably less that that of cintillation detectors, the generally much smaller background corrections required 'hen resolution is high means that one may obtain satisfactory results with lower fficiency.

Elements that may be measured by high-energy gamma-ray spectrometry are otassium, thorium (by measurement of 2.614 *MeV* radiation from ^{208}Tl), and uranium ›y measurement of 1.764 *MeV* radiation from ^{214}Bi; Wylie, 1984, Ch. 2, Ch. 9). If the ranium decay series in not in equilibrium, uranium may be measured by using a igh-resolution detector to distinguish the gamma-radiation of ^{234m}Pa, which should lways be in equilibrium with ^{238}U (Tanner, 1982). A high-resolution detector would also ermit direct detection of low-intensity gamma radiation from ^{235}U. Because high-›solution detectors have relatively low efficiency, and because the relative intensities of ıe emission lines of ^{234m}Pa and ^{235}U are low, the time required to measure uranium irectly (or almost directly in the case of ^{234m}Pa) is much longer than the time required measure the activity of ^{214}Bi. Unless uranium is present in greater-than-normal mounts in subsurface rocks, direct measurement of the element could be done only at xtremely low logging speeds or, more reasonably, by stationary measurements.

The only element within the natural decay series that was on the list of elements of terest to the sponsor is radium. The radiation from ^{214}Bi should more closely reflect e distribution of radium than that of uranium when these are out of equilibrium. owever, the mobility of radon may be such that the ^{214}Bi radiation may not provide a ery useful measure of radium distribution. The only way to measure radium directly by amma-ray spectrometry is to measure with a high-resolution detector the energy at 186 e*V* due to the superimposed weak lines from ^{235}U and ^{226}Ra and then calculate the ontribution of radium by difference,. having determined the uranium activity indepen- ently. This procedure may not be of value in cases where the radium concentration is onsiderably below the equilibrium value.

A variety of sondes for natural gamma-ray spectrometry are in use by various ell-logging services, including scintillation-detector tools of sufficiently small diameter be used within two-inch tubing. EG&G ORTEC offers a shallow-hole probe having a oaxial germanium detector, which may be used in holes having three-inch or greater iameter to depths up to 100 feet. Sondes having germanium detectors that will operate t greater depth are not routinely available, but such devices can be manufactured to rder. The necessary cooling of the detector in such a sonde my be provided by a elting cryogen (*e.g.*, melting propane) or by liquid nitrogen (Wylie, 1984, p321 ff.); for hallow boreholes (not more than a hundred meters deep) liquid nitrogen would be the oolant of choice. Sondes having high-resolution detectors have not been made with a iameter small enough for use in two-inch tubing, because the sensitivity of such a mall detector is not considered to be adequate. However, one might consider use of uch a detector in shallow boreholes where extremely low logging speeds or stationary easurements would be reasonable.

.1.1.2. Low-energy gamma-ray spectrometry

Low-energy gamma-ray spectrometry would be required to detect certain of the termediates in the natural decay series, which would be important when the series are ot in equilibrium (Tanner, 1982). Certain artificial radionuclides might also be detected ith such a spectrometer, which requires a semiconductor detector in order that the w-energy peaks may be distinguished from background. The effective range for such amma-rays is much less than that of high-energy gamma rays, so that this technique ay not be useful in cased or water-filled holes (unless the species of interest is in olution). Unless there is interest in measurement of intermediates in the natural decay eries (other than radium) or of artificial radionuclides that may only be measured by w-energy gamma-ray spectrometry, it is not evident that such a tool would be ecessary for logging natural and artificial radioactivity underground.

.1.2. Prompt gamma-ray spectrometry

The term **prompt gamma radiation** refers to the virtually instantaneous gamma adiation that occurs when neutrons interact with nuclei to produce nuclear excited tates. Such excited states may result from inelastic scattering of fast neutrons or from eutron-capture reactions, which largely involve thermal neutrons. Tools for prompt amma-ray spectrometry include a source of neutrons and a high-energy gamma-ray etector. The neutron source may be either an isotopic source or a neutron generator. neutron generator has the advantage that the neutrons may be pulsed so that lectonic gating may be used to separate the radiation produced by interactions of fast eutrons from that produced by capture of thermal neutrons (Grau and Schweitzer, 987). However, more interfering reactions occur when generator-produced neutrons re used, since they have higher energy than neutrons from isotopic sources. [Better formation on rock porosity may be obtained with a pulsed neutron source than with an sotopic source (Stromswold and others, 1989). Such information is essential for ac-urate estimates of elemental abundances from neutron-induced gamma-ray spectra.] cintillation detectors are used for prompt-gamma spectrometry in well logging for the etroleum industry. Since these detectors have relatively low resolution, a great deal ore information about element concentrations may be obtained if a pulsed neutron ource is used than if an isotopic source is used, but the necessarily greater complexity f such tools means greater cost. Use of a germanium detector would provide better ccuracy in the determination of elemental abundances and would also allow this chnique to be applied to a somewhat wider range of elements than is possible with a cintillation detector. Furthermore, with a high-resolution detector, the advantages of a ulsed neutron source relative to an isotopic source are not so important, so that there ay be a considerable saving in cost of equipment (aside from the somewhat higher ost of the detector itself).

.1.2.1. Prompt gamma radiation from inelastic scattering of fast neutrons

Prompt gamma rays produced by inelastic scattering of fast neutrons provide the est way to measure carbon in subsurface rocks and the only way to measure oxygen. lthough oxygen is not on the sponsor's list of elements of interest, it is the most bundant element in most rocks and its quantitative measurement provides information bout the lithology of subsurface formations that may be indispensable for accurate alibration of measurements of other elements. The carbon/oxygen ratio is an important ey to identification of coal and limestone beds.

Because of the importance of the carbon-oxygen ratio in oil-well logging, a variety f devices are available for carbon/oxygen logging (Bateman, 1985b, pp. 10-11). Dress- r Atlas uses a 3 7/8-inch diameter device for carbon/oxygen logging. Schlumberger /ell Services measures carbon-oxygen ratios with a tool known as IGT (inelastic amma tool). These devices, which count pulses from scintillation detectors in several nergy windows but do not record the entire gamma-ray spectrum, also provide nformation about ratios of certain other elements that are normally present as major onstituents of the subsurface rock or fluid and which produce high-intensity gamma adiation by capture of thermal neutrons (see below). These elements are hydrogen, ilicon, calcium, iron, chlorine, and sulfur. The logs obtained with such tools permit one o distinguish coal and carbonate rocks from ordinary rocks and to estimate the amount f silicates in the coal (ash content) and in the carbonate. The sensitivity for sulfur is not dequate to be useful for measuring sulfur in coal unless long-duration stationary neasurements are done (see below).

.1.2.2. Prompt gamma radiation from neutron-capture reactions

Prompt gamma rays produced by neutron capture reactions are generally useful or determination of the major constituents of rock. The elements that may be deter- nined include silicon, calcium, iron, magnesium, and aluminum, which are commonly najor constituents of rock, and carbon, hydrogen, chlorine, and sulfur, which are major onstituents of certains kinds of rock. Other minor or trace constituents of rock that night be determined by their neutron-capture gamma-rays include vanadium, chromium, nanganese, nickel, copper, boron, and cadmium (which are on the list of elements that re of interest ro the sponsor).

Techniques have been developed to deconvolute the prompt gamma-ray spectra btained with scintillation detectors, so that the abundances of the elements that are the ıajor contributors to these spectra may be determined (Grau and Schweitzer, 1987). uch techniques promise to be of major importance in oil-well logging where knowledge f the abundances of major rock constituents can be of great importance but knowledge f minor- element abundances is not important and where harsh environments in deep ells make use of high-resolution detectors impractical.

In situtations where a high-resolution detector may be used, it should be possible › determine the relative concentrations of the major constituents of subsurface rock ıore accurately with such a detector than with a scintillation detector, and it should be ossible to distinguish the spectral lines of minor constituents that have either a high eutron-capture cross section (*e.g.*, vanadium) or which may be present in greater-ıan-normal concentrations. For elements such as boron and cadmium that have xtremely high capture cross sections but extremely low normal abundances in rocks, nusually high concentrations would be easily detectable. The ability of a logging tool to etect and measure elements other than hydrogen, silicon, calcium, iron, and chlorine or which the capture gamma radiation is normally relatively intense) depends strongly n the time factor. Stationary measurements of long duration can maximize the ability to etect minor elements. Senftle and Mikesell (1987) have shown that sulfur in coal can e determined with reasonable precision from ratios of spectral intensities of gamma ıys produced by neutron capture by sulfur and carbon, if stationary measurements of ›ng duration (20-60 minutes) are used.

.1.3. Activation gamma-ray spectrometry

Many radionuclides produced by neutron capture (or by other reactions with eutrons) decay with the emission of gamma rays of sufficient energy that the activation roducts in subsurface rocks might be detected by gamma-ray spectrometry. Although eutron-activation techniques are not easily adaptable for continuous logging, and so ave not been used routinely in well-logging operations, such techniques do provide an pportunity for measurement of a number of elements that cannot be measured by other ıclear techniques. Generally, because of the wide range in half-lives of the activation roducts, a particular activation procedure can be optimal for only one or a few pecies. Furthermore only a few elements have both an appropriate half-life (a few ninutes) and sufficiently great (normal) abundance and/or reaction cross section that a ontinuous-logging mode can be employed for their determination by neutron-activation nalysis (Wylie, 1984, Ch. 12).

Optimal measurement of the widest possible range of elements by neutron activa- ion would require that widely different periods of neutron irradiation be followed by omparablly variable periods for aquisition of spectral data. Stationary measurements ather than continuous logging would be necessary. Such requirements may be imprac- ical for work in deep holes, but work in shallow boreholes is not nearly so restrictive in his respect. When the thickness of the zone to be explored is only a few tens of meters nd when tools can be lowered into and removed from a hole quickly, it should be ractical to use stationary measurements for neutron-activation work and to design them o that they can be effective for more than just a few elements.

Mikesell and Senftle (1988) have said that about 30 chemical elements are menable to detection and measurement by borehole neutron activation, but their tatement refers to those elements determinable from their prompt gamma rays as well s those where a nuclide that emits delayed gamma rays is produced. Published lists of lements that are determinable by neutron activation in the latter sense (delayed gamma ays) are different from one paper to another, because the possibility of detecting or neasuring a particular element will depend on many variable factors (especially, ntensity of the neutron source, period of irradiation, period of data acquisition, resolution f the detector, and, of course, abundance of the element in the material to be nalysed). Aluminum, manganese, and vanadium will be found on all such lists because hey each have a favorable set of values of the important properties abundance, eaction cross section, and half-life of the activation product. Other elements (from the ist of elements identified as of interest to the sponsor) that should be detectable by delayed) neutron activation are sodium, chlorine, magnesium, and calcium (Hertzog, 1988). Copper, cadmium, selenium, barium, molybdenum, and uranium should also be letectable by this method (Wylie, 1984, pp. 196-198), particularly when they are present n greater-than-normal concentrations.

Other elements might be detected by neutron activation if special equipment or rocedures are used. Detection of cobalt would be possible with high sensitivity if a ow-energy gamma-ray spectrometer is used. Fluorine and possibly even lead might be letected from very short-lived nuclides (half-lives less than 10 seconds) produced by neutron reactions during very brief irradiations. Some elements with rather long-lived ctivation products (for example, arsenic) might be detectable if exceptionally long ounting periods were possible. **Although there are many possibilities for detection of lements by neutron-activation analysis, it must be emphasized that many of the lements on the sponsor's list of elements of interest occur in ordinary rocks only in aces (Krauskopf, 1979, pp. 544-546). For these it is not clear that activation nalysis would be useful, except in a few very favorable cases.**

Generally, isotopic sources of neutrons such as ^{252}Cf are preferable to neutron enerators for neutron-activation work, because the high-energy neutrons from a generator cause too many interfering reactions (Senftle and Mikesell, 1987). The greater rate f production of neutrons from a generator may be useful in cases where it is necessary activate a long-lived nuclide; in such a case the high-energy neutrons would not terfere in the severe ways that they do when short-lived nuclides are to be measured. Ial(Tl) scintillation detectors can be used for particular applications (Senftle and likesell, 1987), but high-resolution germanium detectors will provide a much better apability to resolve the components of the gamma-ray spectra produced by the large umber of activation products that will be produced by neutron activation of rocks.

Senftle and Mikesell (1987) have shown that most of the concern about accuracy f calibration of tools for borehole neutron-activation analysis (involving both prompt and elayed gamma-rays) can be avoided in situations where it is appropriate to use what ey call the **nuclear ratio technique**. In the applications that they have described, the ariable abundance of one element is determined relative to that of another element that a major constituent of the subsurface rock. If the absolute abundance of the major lement may be estimated with reasonable accuracy, and if it is activated by the same ortion of the neutron energy spectrum as is the element whose concentration is ariable, then the nuclear ratio provides a basis for a reasonable estimate of the bsolute abundance of the latter element. This technique is not intended to provide bsolute abundances of high accuracy, but rather it was suggested by the authors to be very useful technique in applications such as exploration for minerals where high ccuracy is not needed. It should be noted, however, that the nuclear ratio technique ould provide a basis for **high precision** measurements of temporal changes in the mounts of certain elements in the subsurface environment. For example, if nuclear atios of manganese and aluminum were determined at one time and then again at a ter time at the same subsurface point, any differences could reasonably be attributed a variation in the manganese content of the rock or soil. Aluminum is a relatively ımobile, major constituent of rock and soil whose abundance at a particular point elow ground should not change appreciably over the lifetime of a test well (assuming ıat the borehole is physically stable).

.1.4. Photoneutron measurement

The only nuclear well-logging technique capable of measuring beryllium, is mea-ırement of photoneutrons produced when gamma rays are absorbed by beryllium uclei. The method has the capability to clearly distinguish beryllium-bearing zones hen ore concentrations are of the order of 1% beryllium, with uncertainties of 0.003% eryllium if a strong (50 *Ci*) ^{124}Sb source is used (Wylie, 1984, pp. 265-266). Since there re no interfering reactions, it would appear that this technique might be useful for ıeasurement of beryllium as a trace element at the part-per-million level, if extremely ›w logging rates or stationary measurements were employed.

.1.5. X-ray fluorescence techniques

A downhole x-ray fluorescence device (Wylie, 1984, pp. 247-259) might permit ıeasurement of a number of elements that are of interest to the sponsor and which are ot practically detectable by any other nuclear technique. Such elements are arsenic, romine, lead, mercury, and strontium. The range of x-radiation is very small compared ı that of energetic gamma radiation, however, so the technique could only be used to ıeasure elements in a very thin layer of rock at the walls of uncased boreholes. xcepting strontium, the normal abundances of these elements in rock are so low that ıey could not be measured adequately with this technique. An x-ray fluorescence ›chnique might be used to measure some of the major species in solution in water ithout interference from materials in the rock. In particular, calcium and chlorine in olution might be measured in this way.

1.6. Cherenkov radiation measurement

Larsen and others (1989) have described a detector developed at Oak Ridge ational Laboratory for field surveillance of radioactivity in groundwater in wells that are ree inches or more in diameter. The detector senses Cherenkov radiation produced / energetic beta particles and (indirectly) by gamma rays in an aqueous medium, but ıs little capability to distinguish among different sources of such energetic radiation at might be present in subsurface water.

Although Larsen and others (1989) have suggested that the detector would be seful to measure ^{90}Sr when it is in equilibrium with its daughter ^{90}Y, it seems unlikely ıat ^{90}Y would be in equilibrium with its parent in groundwater. However, in cased wells here flow is nil over a period of days, ^{90}Y may remain in the vicinity of its parent.

When no artificial radionuclides are present, most of the important species that mit energetic beta particles are nuclides that follow radium in the natural decay series f uranium and thorium. (An exception is ^{234m}Pa.) Since most of these energetic-beta mitters form and decay rather quickly (mostly within one hour in the uranium series and ıostly within one day in the thorium series) after the decay of their radium or radon recursors, the Cherenkov detector might provide useful information about the levels of adium and radon in water within cased wells where the water has not been flowing. The etector itself could not distinguish between daughters of ^{222}Rn (uranium series) and aughters of thorium-series radium, but stationary measurements repeated over a eriod of time (one hour or less) before and after degassing of the well water to remove adon might allow activities of the two different series to be differentiated.

.2. Nuclear Measurements that Provide Information on Physical Properties

.2.1. Gamma-ray backscattering

Measurement of back-scattered gamma rays has long been used to obtain ıformation about the density of the materials in the subsurface environment. The amma radiation appropriate for this purpose is in the energy range 0.3 to 1 *MeV*, here Compton scattering is the predominant mechanism of attenuation of the radiation. he degree of Compton backscattering is a direct function of the electron density of the ıaterial rather than of the mass density, but mass density is very nearly proportional to lectron density in common rocks. Hydrogen-rich materials such as water and coal ave a ratio of mass density to electron density that is smaller than that of common ɔcks, and rare rocks that are exceptionally rich in heavy elements have a larger-ıan-normal value for this ratio (Wylie, 1984, p. 219 ff.).

There are a variety of ways to enhance the amount of information that can be ɔtained from gamma-ray scattering. Most important of these appear to be the simulta-ɘous use of detectors that are at different distances from the source and the use of ɔectral information about the scattered radiation rather than just the total count rate. he intensity of scattered radiation at low energies where photo-electic absorption is nportant is quite sensitive to the abundance of heavy elements (Ellis, 1988; Gadeken nd others, 1988). The spectral information can also be used to determine variations in orehole diameter in cases where it is impractical to use mechanical calipers (Wylie, 984, pp. 231-233), a capability that may be quite important when boreholes have been ased.

In respect to the goals of the sponsor of this research, the main benefit that would e obtainable from a gamma-ray backscattering log would be the information on orosity of the rock, which is of some value in estimating thermal-neutron fluxes as a inction of distance from the source in neutron-activation work. Should the sponsor also e interested in obtaining information about the hydrogeological properties of the ubsurface rock, there would be greater reason to use gamma-ray backscattering logs.

.2.2. Neutron scattering

Logging tools that measure scattered neutrons can be designed so that they are rtually specific for hydrogen, as long as no elements that strongly absorb thermal eutrons are present (Wylie, 1984, p. 151). The information about the hydrogen content f the medium, and about the distribution of thermal and epithermal neutrons within the nedium surrounding a neutron source, can be enhanced by using detectors that espond selectively to thermal and epithermal neutrons and by using detectors at ifferent distances from the source. The sort of information that neutron-neutron probes rovide about the diffusion of neutrons in the subsurface medium would appear to be ssential in any program in which absolute abundances of elements are to be determined directly by prompt gamma-ray logging or by neutron-activation logging. Recently eveloped instruments for neutron porosity logging (Stromswold and others, 1989) and ew techniques for interpretation of neutron porosity logs (Galford and others, 1989; artner, 1989) promise to make such information more accurate than it has been in the ast.

.3. Non-Nuclear Logging Methods

3.1. Caliper logging

Information on variations in borehole diameter is essential in any program where amma-ray spectral intensities are to be used to directly calculate absolute abundances elements in subsurface rock. In uncased holes, mechanical calipers (which might se a radiometric principle for readout; Wylie, 1984, p. 263) can be used to obtain formation on variations in borehole diameter. But the same information can be otained more conveniently with a well-designed gamma-ray backscattering tool, which ould be useful in cased holes as well as uncased ones.

3.2. Other logging techniques

Logging tools of many kinds are used in the petroleum industry to determine nysical characteristics of formations, formation fluids, borehole casing, and borehole uids, as well as to monitor fluid flow in producing wells (Bateman, 1985a, 1985b). Most these specialized logging methods would not be useful to enhance the accuracy of hemical information obtained by gamma-ray spectral logging, particularly when the ork is done in cased holes. Several of these methods are worth mentioning, however. emperature logs that record very slight changes in tenperature of the water in a well an provide information about water flow at low rates. Flowmeters can also be used to leasure water flow. (Information about water flow rates would be quite important henever measurements of radioactive daughters in water are to serve as an indirect leasurement of a longer-lived radioactive precursor.) Inductive logging provides a leans of determining conductivity of formation fluids with a tool in a cased borehole. ata from an induction log could be useful in establishing variations in salinity of roundwater, although there are nuclear techniques that could serve the same purpose Charbucinski and others, 1988).

Many of the non-nuclear logging techniques that are used in the oil industry, cluding particularly electrical and acoustic methods as well as those methods men-oned in the preceding few paragraphs, have proven to be useful in hydrogeological vestigations (for example; Crowder and others, 1988; Paillet and Kim, 1987; Paillet and thers, 1987). There are also a few techniques, such as televiewer logging, that are not ormally useful in oilfield work but are useful in hydrogeology. It has not been our urpose to review such well-logging methods for the sponsor. However, we should point ut that while hydrogeological information may not be necessary for interpretation of the ccuracy of the chemical data obtained by nuclear logging methods (except as noted in e preceding few paragraphs), it may be very important to interpretation of the geo-nemical significance of the data on elements that are mobile in the subsurface nvironment.

3. AVAILABILITY AND COST OF EQUIPMENT AND SERVICES

.1. Standard Pricing Procedures for Wireline Logging

Standard pricing procedures for wireline logging, which are determined primarily y the demand for such services in petroleum exploration and production, include a ne-time set up charge per location plus a depth and operation charge for each service rovided. There is also a charge for interpretation or analysis of the data.

The depth and operations charges include a minimum price based on 1000 feet or 000 feet, and there would be an additional charge per foot of data obtained beyond the iinimum. An example of minimum charges follows:

Set up charge		$ 1065
First log:	Depth	760
	Operation	760
Second log:	Depth	600
	Operation	600
TOTAL (exclusive of tax)		$ 3785

variety of extra charges might apply in a particular case. There are extra charges for ork in remote locations and for any other out-of-the-ordinary difficulties.

.2. Equipment and Services for Gamma-Ray Logging with High-Resolution Detectors

The major wireline-logging service companies have not included logging with gh-resolution detectors among the services provided to the petroleum industry. chlumberger has been doing research on the applications for such detectors, and we ave been told (but we have not confirmed) that Schlumberger has several logging ondes with high-resolution detectors in operation for mineral-exploration applications in anada.

Greenspan, Inc. of Houston,Texas has built a radionuclide logging system that cludes a high-resolution detector and a unique device for cooling the detector with quid nitrogen. The company will provide all the hardware and software necessary for peration of the logging system, including truck and cable, but does not provide a gging service. One such system has been built for DOE work at the Hanford site and owned by Westinghouse. We understand the cost of such a system to be roughly ne-quarter million dollars, but we also understand that a system for work in very nallow holes could be provided at a considerably lower cost.

Radiation Data (formerly PGT Geophysical Services Division), which has a re- ional office in San Antonio, Texas, provides a logging service in which a cryogenically ooled germanium detector is used with a complete analytical system that includes a 000-channel analyser downhole. The equipment is designed for and primarily used for ranium logging, but the system can be used to acquire complete 4000-channel ulse-height spectra. A ^{252}Cf neutron source can be used with the detector to analyse r iron, hydrogen, silicon, chlorine, sulfur, calcium and a few other elements on the asis of detection of prompt gamma rays produced by thermal-neutron capture and by elastic scattering. Logging charges are time-related (not by the foot). Generally, for a ne-week trial the charge would be between $2500 and $3000 per day, which would clude all expenses for the two-person crew, but there would be in addition a mobiliza- on charge of $2.50 per mile for moving the truck from Texas to the logging site and for e return to Texas. Service would be available on reasonably short notice, since the ranium industry is currently in a depressed state.

EG&G ORTEC manufactures a shallow-hole probe equipped with a high-resolution etector, cooled by liquid nitrogen, in which the only down-hole electronics are a reamplifier and high-voltage filter with high-voltage cutoff protection. The device is tended for high-resolution spectrosopy at depths not more than 100 feet and having a inimum inside diameter of 3 inches.

Smith and others (1988), of Kaman Instrumentation Corporation, Colorado Springs, olorado, have recently described small neutron generators that can be used in oreholes with inside diameters as small as two inches. These devices, small accelera- rs that produce neutrons by a nuclear fusion reaction between deuterium and tritium, ave been available for several years for integration into logging probes. Gearhart dustries, Inc. of Forth Worth, Texas manufactures neutron generators that operate on e same principle (Stromswold and others, 1989). We do not have any information on e cost of such devices.

3. Facilities for Calibration

The American Petroleum Institute has maintained for 30 years a facility at the niversity of Houston for calibration of gamma-ray logging instruments and instruments r neutron porosity logging. More recently, a special facility for calibration of gamma-ıy **spectral** logging devices has been added (Tittle, 1989).

Arnold and Butler (1988) have recently described logging calibration technology nd facilities. The U.S. Geological Survey has been active in calibration of devices ıitable for mineral exploration (Mikesell and others, 1986) and for hydrological applica-ons (Hodges, 1988). The calibration procedures and facilities that have been used by e Geological Survey are more likely to be appropriate for the shallow-borehole work at might be useful in environmental-monitoring applications than would be the API cilities.

4. RECOMMENDATIONS FOR FUTURE WORK

This study was stimulated by the interest of Southern Company Services staff in ›veral potentially beneficial applications of nuclear borehole logging. Information was ›quested for the following applications:

(1) exploring for mineral deposits such as coal and limestone;

(2) distinguishing between fresh and brackish groundwater near facilities:

(3) monitoring for groundwater pollutants associated with coal piles, ash and other solid wastes, and wastewater;

(4) monitoring for radionuclides of power-plant origin, as distinct from naturally occurring radionuclides.

›enefits anticipated from applying this technique include opportunities for collecting ›al-time information, monitoring continuously, and viewing large subsurface regions at ›wer cost than by core analyses. It was recognized that such applications would have be selected carefully because this type of logging requires complex data analysis ›d is expensive.

The completed literature survey found sufficient information for all four topics to ›ovide decision-making guidance. We have presented the state of the art in the ›eceding sections, and have given references for descriptions of these techniques as ›ell as specific systems, measurements, and data analyses. Of particular interest are ›cent applications of high-purity germanium detectors with thirty-fold better resolution ›an older sodium iodide scintillation detectors, and of an *in-situ* Cherenkov radiation ›tector for energetic beta particles from radionuclides in groundwater.

With this information at hand, one needs to determine case by case whether any the measurement techniques is feasible and practicable for a specific substance at e concentration of interest in the soil matrix under study. Feasibility is determined by ›amining the pertinent parameters for detection and analysis systems that are available may be constructed. These parameters define the detection limits and measurement ncertainty as functions of concentration for the substance of interest and interfering naterial, operational aspects of the system such as travel rate and counting period, and ata analysis algorithms. Some of this information is in the cited publications, but arameters for many substances and conditions will have to be calculated or estimated.

The first step in this process is to identify specific sites and substances as test ases, and to select a logging system, operational parameters, and data analysis rograms for reference calculations. Soil and system characteristics will determine hether data of sufficient sensitivity and precision can be generated. This information an be derived for the generic situation, but is far more appropriate when obtained from ite-derived — *i.e.*, core sample — data and from logging system tests at comparable ites. This evaluation may conclude that the logging system is suitable, or is insufficiently sensitive, or should be reevaluated under revised operational parameters.

If nuclear borehole logging is predicted to be feasible for the test site, further fforts should then be devoted to confirming the prediction, estimating the cost of the gging program, selecting a suitable system, and comparing the cost, effort, and esulting information to alternative measurement programs. The most direct confirmatory ffort would be a brief logging test at selected boreholes. A contractor may provide a alibrated detection system, or a system may be developed in-house with appropriate tercalibration and quality control. Comparisons with core samples are useful to onfirm the calibration and examine the impact of matrix nonuniformity. Ancillary characterization of the soil matrix with various non-nuclear borehole logs may be desirable adjust the computational model for site conditions.

This step-wise approach should assure that nuclear borehole logging has a easonable chance of success and is cost-effective. Under conditions for which this chnique appears to be only marginally useful, the approach may suggest how esearch and development efforts could yield improvements. Finally, where applications re prevented by insufficient sensitivity or serious interferences, the approach avoids asteful commitment of funds and efforts.

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6. ANNOTATED BIBLIOGRAPHY

. Instrumentation

.1. Nuclear logging tools

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ısTRACT

This paper describes current techniques for performing natural gamma ray spec-scopy measurements in borehole environments. The data were obtained using the stem known as the Compensated Spectral Natural Gamma tool which uses the com-ete energy spectrum to provide information on the borehole environment in addition to ncentrations of potassium (K), uranium (U) and thorium (Th) in the formation. Elemental ncentrations are estimated from count rates in thirteen selected energy ranges indows) using the method of weighted-least-squares which incorporates real-time com-nsation for borehole effects. This is accomplished by using an attenuation model which counts for count rate reduction and spectral shape changes due to borehole absorption d scattering. The use of a low atomic number toolcase allows gamma rays in the low ergy, photoelectrically sensitive part of the spectrum to be transmitted to the detector. e system gain stabilizer operates in a coincidence mode so that the formation gammas cident on the detector can be separated from those which originate in the ^{241}Am ıbilization source. This low energy data is processed into ratios of Compton and otoelectric window count rates. The ratio in uncased holes is optimized to provide alitative indications of lithology and changes in lithology. A similar ratio in cased wells 'es diagnostic information regarding the condition of the steel tubulars in the borehole. 'o examples demonstrate the presentation of the logs and the quality of the results.

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This paper shows the sensitivity of a large detector for trace amounts of Th and U d indicates how compensation for variability in lithology or casing can permit accurate ıasurement of these elements and of potassium at a logging speed of 10-12 feet per nute. The paper has information on how the instrument is stabilized and calibrated and how a "quality log" is obtained to ensure the accuracy of the response and to provide timates of the uncertainty of the measurements. [JMW] rsen, I. L., Chiles, M. M., and Miller, C., Development and fabrication of an *in situ* Cherenkov radiation detector, *Nuclear Instruments and Methods in Physics Research, A279*, 665-667, 1989.

STRACT

A detector has been developed for field surveillance of radioactivity in groundwater wells that are 7.6 *cm* in diameter or larger, but it can be adapted to on-line monitoring industrial waste effluents and municipal water treatment plants, as well as facilities that ocess chemical and nuclear wastes. The detector utilizes the principle of direct erenkov radiation counting of energetic betas and gamma-rays in an aqueous medium. r 90Y in equilibrium with its parent ^{90}Sr, the response of the detector was linear with reased concentrations. The estimated detection limit for ^{90}Y supported by the parent r is 1 *pCi/ml* for a 1000 *s* counting interval.

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The method has little capability for distinguishing among different sources of ergetic betas that might be present in subsurface waters. The authors do not address question of why one might expect ^{90}Y to be in equilibrium with its parent in subsurface ters; it seems likely that yttrium would be rather quickly adsorbed on solid surfaces derground, so it is not clear that the method would be useful to measure levels of ^{90}Sr subsurface water. [JMW] omswold, D.C., Mills, W.R., Wilson, R.D., and Cook, T.K., Formation porosity measurement using epithermal neutron lifetime. *IEEE Transactions on Nuclear Science, 36,* 1210-1214 , 1989.

STRACT

A logging tool for in-situ measurement of earth formation porosity using epithermal utron lifetime has been constructed and tested. A 14-Mev neutron generator in the tool nits pulses of neutrons and a Gd-covered ^{3}He counter detects neutrons returning from formation as a function of time following the emission pulse. Counts are accumulated 200 1- s-wide channels for repeated pulses of the source. Tests of the logging tool in mation models of known porosity and in oil wells indicate superior porosity sensitivity d decreased lithology (rock type) dependence compared to methods using steady-state urces. Computer modeling using the time-dependent Monte Carlo Neutron Photon CNP) code has provided lifetimes which support and extend measurements made with tool. MCNP results from a three-dimentional model of the logging tool eccentered in a rehole have yielded excellent agreement with actual tool measurements.

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The experimental logging tool is referred to as "Pulsed Neutron Porosity" (PNP). e tool has a diameter of about 9.5 cm and a length of 0.5 m. The accelerator produces -MeV Neutrons through the D-T reaction [^{3}H(^{2}H,n)^{4}He] in a neutron generator tube anufactured by Gearhart Industries, Inc., of Fort Worth, Texas. Three ^{3}He detectors vered with gadolinium foil are positioned side-by-side near the surface of the logging ol that touches the borehole wall. The detectors are 1.11 x 15 cm (I.D. x L) each and ey are filled with 10 atm of gas. Gd foil 0.0015 cm thick covers each detector to absorb ermal neutrons, which allows more lower energy (down to 0.15 eV) epithermal neutrons reach the detectors. There is an excellent agreemnent between the experimental sults and the MCNP simulation of the PNP tool. [HG]

.2. Electronics and components

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STRACT

Barium fluoride and cadmium tungstate have previously been used as radiation tectors in a number of applications such as high energy physics and tomographic aging. The fundamental properties of these materials, with particular attention to propies relevant to nuclear well logging applications and their temperature dependance ve been studied. Both detectors have properties that would seam to make them useful specific logging measurements. However, using these materials requires overcoming ier properties that limit their usefulness. For example, barium fluoride has a fast iission output that lends to high counting rates. The intensity of this emission, however, very weak and, in addition, is at a wavelength not efficiently detected by common iging photomultiplier. Cadmium tungstate's high density and atomic number give exllent detection efficiency, but its application in well logging are limited by its long ntillation decay constant.

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The scintillation decay time of the emission component at 220 nm of barium fluoride less than 1 nanosecond. It is much faster than that of any other known inorganic ntillator and is even faster than most plastic scintillator. In addition the intensity of this iission is totally temperature independent. The primary interest in cadmium tungstate s in its high detection efficiency which results from a high density and high atomic nber. Using a Monte Carlo calculation, the detection efficiency at 2.6 MeV of cadmium gstate is about 3.2 times of that of NaI. However because of its slow decay time nstant it is limited its usage to low count-rate measurement such as natural activity. ually low count-rate applications require large crystal size but cadmium tungstate has or light transmission that limits crystal size for reasonable performance. Barium fluoride s an extremely fast scintillation component useful for fast count-rate measurement, but emission (220 nm) is weak and must be separated from the slower 310 nm emission. G] ıith, R. C., Bush, C. H., and Reichardt, J. W., Small accelerators as neutron generators for the borehole environment, *IEEE Transactions on Nuclear Science, 35*, 859-862, 1988.

ɜSTRACT

Small-diameter, electrically-operated, pulsed neutron sources have many present d potential applications in borehole measurements. These include thermal neutron ɛtime measurements, using pulse rates in the 1000 *pps* range, and fast neutron inelastic attering approaches, using pulse rates in the 20,000 *pps* range. For several years a utron generator suitable for these applications has been available for integrating into ers' systems. Based on the D-T fusion reaction, it produces neutrons at the 108 *n/s* ɾel in a 1 11/16 in. diameter package. It operates in environments up to 150°C and up to ,000 *psi*. Experience with this system is described including factors, such as He-3 gas ildup, that limit the life of its sealed accelerator tube. Design improvements of this stem, aimed at increased environmental temperatures are also discussed. COMMENTS is is a description of a commercially available neutron generator having a diameter ıall enough that it could be used in two-inch boreholes. The generator is normally nfigured to operate at 1000 pulses per second with pulses of about 100 microsecond ration; in this mode it is useful for determining the decay time of thermal neutrons in the rehole environment, thus to distinguish chloride-bearing brines from from fluids that do t capture neutrons so readily (*e.g.*, petroleum or fresh water). The device may also be ed to produce 5-microsecond pulses at a rate of 20,000 pulses per second for the rpose of obtaining fast-neutron inelastic scattering logs; such logs can be used to tain information about the carbon-oxygen ratio in rock, and the ratio of calcium to silicon ay also be determined from thermal-neutron-capture gamma rays that are produced in ɜ time interval between pulses. (Operation in this mode requires a larger, more nsitive, detector, configured to provide more information about energy distribution, than ɜ detectors used for thermal-neutron decay-time logs.) It is also possible to run the nerator in a continuous mode for porosity logs, although radioactive neutron sources ɜ more commonly used for this purpose. The neutron generator [Kaman Model A-320 is ɜ one described in the paper] is manufactured by Kaman Instrumentation Corporation of ılorado Springs, Colorado. The electronic control unit may be separated by up to four ɜt from the accelerator head so that detectors may be installed by the user. The lifetime the generator is limited by the release of ^{3}He from the tritiated accelerator target, which ɜults in a typical tube lifetime of between 1.5 and 2 years. We do not yet have ɔrmation on the cost of this neutron generator. [JMW]

.3. Improvements and modifications

een, P.G., and Mwenifumbo, C.J., Interpretation of new generation geophysical logs in Canadian mineral exploration. pp. 167-178 *in Proceedings of the Second International Symposium on Borehole Geophysics for Minerals, Geotechnical, and Ground Water Applications*, Minerals and Geotechnical Logging Society (c/o Southwest Research Institute), San Antonio, Texas.

STRACT

Technological advances in the past few years have led to the development of a new neration of slimhole logging tools for mineral exploration. While some are completely w developments, others are adaptations of technology from surface geological survey- or from petroleum logging. The application of these new geophysical methods requires nsiderable testing and development of new interpretation techniques for the different ological environments encountered in mineral exploration. At the Geological Survey of nada (GSC) one objective of research in borehole geophysics has been to investigate application of these methods to mineral exploration in various mining areas across nada. The GSC R & D logging system has five 'new generation' logging probes which asure thirteen different parameters:

Temperature probe: temperature, temperature gradient;
I.P. probe: I.P., resistivity, S.P.;
M.S. probe: magnetic susceptibility, conductivity;
Gamma Spectral probe: total count, K, U, and Th;
Spectral Gamma Gamma: density, heavy element assay.

amples are described showing interpretations of the logs from various mining areas in nada which include lead, copper, zinc, and uranium deposits.

MMENTS

The GSC logging system is typical of modern digital data acqusition systems being lt around a minicoputer. Data are recorded on 9-track magnetic tape. A digital CRT plays data, spectra, or waveforms. Data input is via modules specific to the parameters ing measured. Detailed interpretations are based on post-processing of the tapes on a bit Data General Corp. MV4000 computer at headquarters. The main characteristics described as:

1. Spectral gamma ray logging tool (O.D. = 32, 38, or 50 mm). Full gamma ray ectra are recorded in 256 channels covering an energy range from approximately 0.1 3.0 MeV. Gamma ray counts in 10 selected energy windows. Usually the largest tector compatible with the borehole diameter is used to give max. sensitivity and ging is done at 3 m/min.

2. Induced polarization (IP/R/SP) logging tool (O.D. = 38 mm) consists of a time- main transmitter, probe electronics and the electrode arrays. There are four selectable se times for the current waveforms; 0.25 s, 0.5 s, 1 s, and 2 s(i.e., full waveform of 1 cond to 8 seconds duration).

3. Temperature logging tool (O.D. = 25 mm) consists of a 10-cm long tip of ther-

stor beads with sensitivity of 0.0001 °C.

4. Spectral gamma gamma (SGG) logging tool (O.D. = 32, 38, or 50 mm) is sentially the spectral gamma ray logging tool in a gamma-gamma density configuration. e probe consists of a 10-millicurie gamma-ray source (Co-60, Cs-137, or Ir-192) and a intillation detector (sodium iodide or cesium iodide).

IT>5. Magnetic susceptibility logging tool (O.D. = 42 mm x L. = 0.5 m). There are 4 nsitivity ranges on this system: 20, 80, 320 and 1280 x 10^{-3} S.I. units, with the highest tting giving a measurement resolution of approximately 0.005 x 10^{-3} S.I. units. Ten amples are illustrated in the paper. [HG]

ᵎ. Interpretation

ᵎ.1. Inversion of nuclear spectral data

ɪrtzog, R., Colson, L., Seeman, B., O'Brien, M., Scott, H., McKeon, D., Wraight, P., Grau, J., Ellis, D., Schweitzer, J., and Herron, M., Geochemical logging with spectrometry tools, *Society of Petroleum Engineers, 62nd Annual Technical Conference and Exhibition*, Dallas, TX, September 27-30, 1987, pp. 447-460.

ɪSTRACT

A Geochemical Logging Tool (GLT)* string, measuring natural, activation, and ɔmpt neutron capture gamma rays, produces logs of the most abundant and a few trace ɪrganic element concentrations. Direct measurements of Al concentrations are pro- ɪed. A geochemically based closure model is used to derive Si, Ca, Fe, S, Gd, and Ti ncentrations. The only significant spectroscopically undetermined element, Mg, is erred by comparing measured to derived photoelectric factor. Analysis algorithms, monstrations of accuracy and precision, and applications of geochemically derived mation properties are discussed.

ɔMMENTS

This is one of several recent papers that describe a recently developed logging ɔl that has a considerably better capability for distinguishing among major elements in bsurface rocks than do the devices commonly used earlier in well logging in the troleum industry. Because the device is physically quite long and because it has been timized for application in the petroleum industry where the logging rate must be large t where the list of elements of interest is limited, the importance of this paper will be marily for the perspective that it gives on what can be done to obtain a maximum ɪount of information from somewhat limited data when there is a strong economic :entive to obtain the information. [JMW] uman, C. H., Salaita, G. N., and Mahdavi, M., Neutron scattering for porosity determination. *IEEE Transactions on Nuclear Science, 35*, 812-816, 1988.

) abstract]

)MMENTS

This paper focuses on the way in which scattered neutrons (epithermal and thermal) y be detected, on the physics of scattering of epithermal neutrons and of the sorption and scattering of thermal neutrons, and on the interpretation of neutron asurements in respect to the amount and character of subsurface fluids in rock pores. hough the paper is primarily about neutron measurement and the interpretation of the utron logs, the authors also give brief consideration to other logging techniques oustic and gamma-ray techniques) that relate to formation porosity. [JMW] nweitzer, J. S. and Ellis, D. V., Review of nuclear techniques in subsurface geology. *IEEE Transactions on Nuclear Science, 35*, 800-805, 1988.

STRACT

Nuclear techniques have assumed a major role in obtaining data on geological ata. These techniques require detailed analysis to understand the meaning of the asurements because of the extended region of the interactions and the complications oduced by the borehole environment. In addition, the nuclear parameters that are asured must be related to the geological parameters that are of interest. Types of asurements that can be performed, their relationship to geological parameters, limita-is imposed by the need to make measurements in extended media under hostile nditions, and methods to analyse the measurements are presented.

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This paper is a review of the ways in which spectral analysis of scattered gamma s, of scattered neutrons, and of natural and neutron-induced gamma radiation may be erpreted to provide information about physical properties and composition of subsur-e formations. This is perhaps the best available recent paper that deals with all of the ds of information that may be obtained from nuclear spectra. It includes an example of pectrum of high-energy capture gamma rays obtained with a high-resolution detector, ich suggests a capability to measure Ni, Co, and Cr, as well as the major elements in k that may be determined with detectors of lower resolution. (In this case, however, Ni, Co, and Cr, were constituents of the cryostat that contained the Ge detector.) AW]

.2. Algorithms and models

cobson, L.A., A matched filter data smoothing algorithm. *IEEE Transactions on Nuclear Science, 36,* , 1989.

STRACT

An efficient spatial smoothing algorithm for filtering data while preserving spatial tail is obtained using the system (impulse response) function of the sensor. In contrast the normal procedure for determining the filter coefficients for an arbitrary system ction, this technique does not use Fourier transforms. The spatial filtering coefficients e obtained analytically for the frequently applicable Gaussian system function. The iciency of this procedure is illustrated by filtering simulation, logs and spectral data. For altime smoothing of nuclear log data, a filter length of 5 times the vertical resolution is quired.

:.3. Calibration

:le, C. W., Model wells for nuclear well logging. *Nuclear Geophysics, 3,* 193-202, 1989.

STRACT

Considerations needed in the design and construction of model wells for nuclear log ibration are covered, with special attention to neutron porosity logging and total γ-ray gging. Pulsed neutron decay-time and spectral γ-ray logging are discussed briefly.

The API calibration facility for nuclear logs is a good starting point for similar or panded facilities. A few of its shortcomings are mentioned; they are minor. The problem fluid saturation is emphasized. Attention is given to models made of consolidated rock d those containing unconsolidated material such as Ottawa sand. Needed precautions e listed. A similarity method is presented for estimating the porosity index of formations t are not fully saturated.

)MMENTS

This recently published paper contains a brief introduction to the various proce-res that are used for calibration of nuclear well-logging instruments and then has a scription of the API gamma-ray and neutron pits that have been available at the iversity of Houston since 1959 for calibration of logging tools that are used in the troleum industry. There is also a brief description of a recently built facility (also at the iversity of Houston) for calibration of natural spectral -ray tools for measurement of tassium, uranium, and thorium. Following these descriptions is a listing of several other ganizations that have calibration facilities that are available for public use. The last ction of the paper is a discussion of factors that are important in the design of a utron porosity calibration facility.

The emphasis of this paper is on calibration of the tools that are most important in clear well-logging in the petroleum industry, in test pits that more closely resemble oil lls than the smaller-diameter wells encountered in mineral exploration and vironmental-monitoring activities. The paper has little information on the new spectral mma-ray calibration facility at Houston and there is no information that pertains directly calibration of tools for spectral measurement of gamma radiation induced by neutrons. t since calibration of tools for spectral logging of neutron-induced gamma rays will rays depend strongly on information about rock porosity and saturation, the calibration)cedures addressed in this paper are important for any logging activity that would use mma-ray spectral information to determine elemental abundances in the subsurface. ΛW]

. Applications

.1 Elemental analysis

Bourayne, Armand M., High resolution spectroscopy for direct uranium ore grade assay in exploration, development and production, pp. 227-240 *in Proceedings of the Second International Symposium on Borehole Geophysics for Minerals, Geotechnical, and Ground Water Applications*, Minerals and Geotechnical Logging Society (c/o Southwest Research Institute), San Antonio, Texas.

STRACT

A conventional gross gamma ray logging detects and measures Bismuth 214 and es to infer the uranium ore grade from the measured bismuth concentration. In an uilibrium orebody it is adequate, but disequilibrium leads to large errors, and disequilib-m is the rule not the exception. COGEMA has developed new system for *in situ* analysis uranium orebodies. COGEMA's probe is capable of quantitative analysis uranium-aring ores containing as little as 100 *ppm* of uranium, even in ores subject to ochemical disequilibrium. The main parts of the system consists of a microcomputer ich drives all the operations and processes data, a main cabinet for nuclear in-umentation, and a control-panel to move the probe in the geological formation inside a sing. At any given depth the COGEMA tool assays a spherical volume that penetrates formation a distance of about 4 inches from the borehole wall. The probe measures a *MeV* gamma ray emitted by protactinium 234 very promptly (a 24 day half life) after the cay of U-238. The logging speed is computer controlled, between 6 to 60 feet per hour. s much faster to measure a rich uranium deposit than to measure a low grade deposit the same precision. Where more precise measurement is reqired longer counting riods are used.

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This paper contains a description of a process developed by COGEMA ompagnie Generale des Matieres Nucleaires) for in situ *analysis for uranium in subsur-e rock, based on high-resolution gamma-ray spectrometry. Emphasis is on the use of a h-resolution probe (HP Ge) to measure the 1.001 MeV gamma radiation from ^{234m}Pa as surrogate for ^{238}U. The process is said to provide quantitative analysis of uranium-aring ores containing as little as 100 ppm uranium. Since the author had no interest in nium as a trace constituent of rock, there is no direct information on the sensitivity of process for trace amounts of uranium. By implication, trace amounts of uranium (via ^{m}Pa) and of the strong-gamma emitting descendents of uranium and thorium could be asured if long counting times are permissible, and ^{40}K could be measured by tection of its 1.461 MeV gamma ray. The process is intended to measure gamma liation from subsurface rock; one would not expect it to be useful for measurement of ural radioactivity in subsurface water, which normally would be at much lower levels n the radioactivity in the rock. [JMW]*

The COGEMA system has several advantages: direct quantitative readout of ura-m content is unaffected by disequilibrium and other geological parameters; it is much s sensitive to nonuniformities in tha formtion than coring. It gives an accurate uranium say in real time, avoiding time delay, the expense and the likehood of errors that occur h coring. Finally it eliminates gaps in the measurements due to lost core sections. [HG] apman, S., Colson, J. L., Flaum, C., Hertzog, R. C., Pirie, G., Scott, H., La Vigne, J., Quirein J., Everett, B., Herron, M. M., Schweitzer, J. S., and Wendlandt, R., Geochemical well logging in early evolutionary stage, *Offshore*, May 1989, 82-89.

o abstract]

OMMENTS

This paper contains a description of the ways in which elemental analysis by three mmercial logging tools (K, Th, and U by natural gamma-ray spectrometry; H, Si, S, Cl, , and Fe by spectrometry of gamma rays induced by pulsed 14-MeV neutrons; and Al neutron activation) can be used to calculate the proportions of the several clay nerals and other minerals that are commonly present in sediments. There is a discus-on of some indirect applications of such mineralogical data that are important in the troleum industry. The paper ends with a box having descriptions of specific applica-ns of measurements of each of these ten elements plus Ti and the rare earths Gd and n and some information about how the elements are measured and on the accuracy of e measurements. [JMW] ‹esell, J. L., and Senftle, F. E., Borehole neutron activation: The rare earths, *IEEE Transactions on Nuclear Science, 35*, 833-838, 1988.

STRACT

Neutron-induced borehole gamma-ray spectroscopy has been widely used as a ophysical exploration technique by the petroleum industry, but its use for mineral ɔloration is not as common. Nuclear methods offer the mining geologist techniques for ıeral exploration, for determining stratigraphy and bed correlations, for mapping ore ɔosits, and for studying mineral concentration gradients. High-resolution detectors are sential for mineral exploration, and by using them an analysis of the major element ıcentrations in a borehole can usually be made. A number of economically important ments can be detected at typical ore-grade concentrations using this method. Because the new application of the rare-earth elements to high-temperature superconductors, se elements are examined in detail as an example of how nuclear techniques can sist the mining geologist.

MMENTS

This paper is particularly important because it emphasizes application of a well-ging technique outside the petroleum industry (i.e., to mineral exploration) and be-ise it emphasizes the importance of high-resolution gamma-ray detectors in such an plication. Although the paper focuses on the application of neutron activation to the e-earth elements, there is an important general portion of the paper that deals with the ɔad range of potential applications of the technique. There is in particular a list of some ty elements that are amenable to detection and quantitative measurement by borehole ıtron activation. [JMW] uman, C. H., Test of a high-resolution spectroscopy logging tool to measure chlorine in a low-salinity reservoir, *SPE Formation Evaluation,* March 1988, pp. 40-46.

STRACT

A series of tests was conducted to evaluate the usefulness of neutron-induced mma spectra recorded by a detector cooled to the temperature of liquid nitrogen. ese tests were conducted in an oil well that had been evaluated with core and other ging techniques. Results showed that measurements of carbon abundance were not curate enough to enable useful estimates of oil abundance, but measurements of orine abundance could be used to estimate brine saturation if data were accumulated g enough.

The commercial logging equipment tested consisted of two different tools that mbined a high-resolution detector with both chemical and 14-*MeV* pulsed neutron urces. Methods were developed to process and display the 4,000-channel spectra corded. Use of the spectral data to measure chlorine abundance was developed by cording spectra at depths opposite formations containing saline and fresh water. Effects brine in the casing were evaluated by recording spectra before and after brine in the sing was displaced by fresh water.

Predicted statistical uncertainty and variations between repeat runs indicated that a asurement of chlorine abundance that discriminates between 30 and 50 saturation ts (s.u.) of oil requires 1-hour station measurements for 11,000-*ppm* brine. Chlorine undances calculated from the spectral data were consistent with saturations measured m cores and openhole logs. Spectra of gamma rays from inelastic scattering of utrons produced by a pulsed source had no detectable carbon peaks.

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This report is an investigation of the use of a high-resolution tool to reflect chlorine undance in a formation having brine fresh enough to preclude use of pulsed neutron oture (PNC) logs. The tool used for the test was developed by Princeton Geophysical rvices Inc. The tool was modified by adding one of two neutron sources: 1) a ifornium-252 (^{252}Cf) source that emits relatively low-energy neutrons continuously (the emical source), and 2) a 14-Mev pulsed source (the pulsed source). Both versions of tool were modified by adding a casing collar locator which made it possible to ntify accurately the depth of formation corresponding to the spectra recorded. The nma rays are superimposed on a continuous background radiation from capture of rmal neutrons.

Statistical uncertainty requires a data accumulation period of one hour to distinguish saturation of 30 and 50 s.u. when water salinity is as low as 1000 ppm. However seven nutes suffices for reservoirs having the same porosity but brine with the salinity of awater. Quantitative measurement requires the displacement of brine from casing or of a fluid excluder which was not adequately evaluated in the test. High-resolution ectra of gamma rays from inelastic scattering of 14-MeV neutrons showed no obvious dence of peaks resulting from carbon for the condition tested. [HG] hweitzer, J. S., Hertzog, R. C., and Soran, P. D., Nuclear data for geophysical spectroscopic logging, *Nuclear Geophysics, 1*, 213-225, 1987

STRACT

Geochemical analysis of subsurface formations can provide significant information out the minerals and the fluids contained in the rock. While most previous work has en based on the analyses of cores, significant advances have been made to provide ch analyses from gamma-ray spectroscopy data obtained in a borehole. Previous work geophysical spectroscopic measurements in a well has largely concentrated on alitative analyis or the detection of ore-grade minerals. A nuclear geochemical analysis, wever, requires the quantitative measurement of elemental concentrations of trace ments, as well as major elements in widely varying concentrations. This requirement ces extreme demands on the quality of the spectroscopic measurements, data rates, d relating observed gamma-ray intensities to the original elemental concentration. The ationship between gamma-ray intensities and elemental concentration is critically dendent on the specific reaction cross sections and their uncertainties. The elements of hest priority for subsurface geochemical analysis are considered with respect to the portance of competing reactions and the neutron energy regions that are most signifint.

MMENTS

This paper is quite important becuase it deal specifically with the neutron-induced actions that may be detected by high-resolution gamma-ray spectrometry for the rpose of determining concetrations of elements in subsurface materials. The authors int out important advantages and disadvantages of various kinds on neutron sources. A Cf source has the great advantage over neutron generators that its relatively low-energy utrons will generate a minimum of nuclear reactions that would interfere with the termination of individual elements. However, such a source is limited in intensity and nnot be pulsed. The advantages and disadvantages of a 14-Mev neutron generator are converse.

The main emphasis of the paper is on the importance of a knowledge of neutron action cross sections for a wide range of neutron-induced reactions that may occur in bsurface materials. The cross sections must be known over the entire range of energy the neutrons, and thus more data are needed in the case of high-energy neutrons from nerators. The cross sections must be know for all of the elements that are present in ficient quantity in the subsurface materials to interact aignificantly with the neutrons. owledge of the uncertainties in the cross sections is essential in determining the certainties in converting spectrometry data to elemental concentrations. Commonly, certainties in cross sections must be compounded in such a way that no satisfactory imate of an element's concentration may be made. [JMW]

.2. Mineralogical composition and physical properties of rock

is, Darwin V., Gamma ray scattering measurements for density and lithology determination. *IEEE Transactions on Nuclear Science, 35,* 806-811,1989.

STRACT

A common approach to determining the *in situ* bulk density of subsurface formations to use gamma ray scattering devices. These well logging tools consist of a source of mma rays and multiple detectors, mounted in an assembly which is kept in mechanical ntact with the borehole wall during the moving measurement. Conpton scattering is ploited for formation density information while analysis of the photoelectric absorption of ltiply-scattered gamma rays provides the average atomic number of the scattering mation.

The parameters which control the device performance, constrained by operation in borehole, are examined. A technique of combining measurements from several tectors allows estimation of bulk density over a range of environmental conditions. The otoelectric absorption measurement is reviewed to indicate its relationship to formation ology type. Borehole factors which may compromise both measurements are related to l design parameters and fundamental physical limitations.

rtl, W. H., and Chilingar, G. V., Total organic carbon content determined from well logs, *SPE Formation Evaluation*, June 1988, pp. 407-419.

IMMARY

Total organic-carbon (TOC) content present in potential source rocks significantly ects the response of various well logs. This paper discusses and illustrates well-log omalies coused by TOC as observed on various wireline measurements, including sistivity (or conductivity), acoustic, nuclear (density and neutron), gamma ray, natural mma ray spectra, and pulsed neutron [sigma and carbon/oxygen (C/O) ratio].

Field examples of these well-log responses in open and/or closed wellbores are esented from several countries. Several correlations between TOC and individual and/or mbinations of various logging responses are also reviewed.

MMENTS

This paper deals with the way in which organic carbon in subsurface rocks affects a iety of nuclear and non-nuclear well logs. Its particular importance in respect to this bject may be that it focuses on the organic carbon in potential source rocks rather than potential production zones. Thus the emphasis is on detection of organic carbon in atively low concentrations, which may relate more closely to some of the potential plications outside the petroleum industry than do most papers dealing with hydrocarn detection. [JMW]

This paper reviewed the field examples of the well-log responses in open and/or sed wellbores from several countries. Several correlations between TOC and individual d/or combinations of various logging responses are also reviewed. For example: highly lioactive, black, organic-rich and gaseous shales exhibit a highly oil-saturated matrix, t is characterized by low values of K and Th, but excessively high bismuth-214.(K, Th d Bi can be measured by natural gamma-ray spectra). Inasmuch as TOC content is ctrically nonconductive, high TOC content can increase the resistivity of the host rock, wever resistivity is not a good TOC indicator. From the pulsed-neutron capture logs, information can be related to the relative abundance of paticular elements, e.g., C, O, and Si. The multiparameter spectroscopy instrument, i.e., MSI-C/O logging instrument, s mentioned. Low density related to high TOC content. TOC content tends to increase apparent interval transit time t value which is measured by acoustic logs. All the amples reviewed illustrate empirical correlations between TOC content and single d/or combinations of wireline logging parameters. [HG] rron, M. M., Future applications of elemental concentrations from geophysical logging, *Nuclear Geophysics, 1,* 197-211, 1987.

STRACT

Measurements of elemental concentrations currently play a very small role in bsurface formation evaluation in the petroleum industry. However, new advances in data erpretation combined with new measurement capabilities indicate that the interest in mental concentration measurements will expand rapidly in the future. Applications can divided conveniently into two general classes relating to the fluids and to the solids. In case of fluids, the major applications are the direct detection of hydrocarbons and of uble impurities in subsurface water. These impurities not only interfere with the detec- n of hydrocarbons by geophysical techniques, but they may also influence the produc- n techniques to be used. New applications have been developed for the use of rganic chemical data in evaluating subsurface solids. These include a new normative alysis which permits a quantitative estimation of the minerals which make up the rock. e element-derived mineralogy permits a significantly enhanced rock description beyond t now available. In addition, the new techniques have applications in such areas as the erpretation of depostitional environment and diagenesis, and the estimation of such rameters as cation exchange capacity, grain size, and even permeability. Elements are ed in order of value to the petroleum industry according to these potential applications order to speed the necessary nuclear measurements to ensure high quality nuclear ochemical data.

MMENTS

This paper deals with the roles that determination of elemental concentrations in bsurface rock (for which there is an existing technology for certain elements) and in bsurface fluids (for which the technology has not been developed) should play in the troleum industry in the future. Applications are classified as direct (which includes ablishing the mineralogy of subsurface formations), indirect, and inferred; many of se applications would not be of interest outside the petroleum industry. The author es an element-by-element listing of priorities for elemental measurement in the petro- m industry. This listing emphasizes how elemental abundance measurements would be ed, not how they could be made. [JMW] yal, J. R., and Christoffel, D. A., Coal quality from geophysical logs: Southland lignite region, New Zealand, *The Log Analyst*, September-October 1989, 343-349.

STRACT

Density, gamma-ray, neutron, sonic, caliper, resistance, self-potential, and focused-sistivity logging were carried out for lignite coal evaluation in the Southland lignite jion. The most useful logs for identification and location of the coalseams were density d gamma-ray. Ash, moisture, volatile-matter, and fixed-carbon content of the cored coal nples obtained by the chemical analysis were correlated with the geophysical log data. h (%) showed strong positive correlations with the density and gamma-ray logs. isture (%) showed strong negative correlation with the density log and positive correla-1 with the sonic log. Volatile matter (%) and fixed carbon (%) showed negative rrelations with the gamma-ray, density, and sonic logs. Stepwise multiple-regression thod was used for developing empirical relationship between coal quality and geophysi- logs. These relationships were very useful for prediction of coal quality with a fair gree of accuracy (mostly within ±1%).

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This recently written article shows the power of well-logging techniques to distin-ish coal (including lignite) formations from ordinary sedimentary rocks as well as to vide information about the quality of the coal. The article includes references to earlier rk on the application of geophysical logs specifically to coal exploration in various ts of the world. The density and natural gamma-ray logs are the most useful of several ds of logs for the purpose of evaluation of coal quality. [JMW]

This article emphasized the generalized empirical relationships obtained for coal-ality estimation with the help of geophysical logs in the Southland lignite region. The ophysical variables that met 5% significance level are used in the prediction models. e coal-quality model is influenced by the different geological/depositional environments tween the marine and non-marine lignites. No well-logging tools were described in the per. [HG]

.3. Character of subsurface fluids

pernaw, I.R. and Richter, A.P., A nuclear salt-in-crude monitor. *IEEE Transactions on Nuclear Science, 36,* , 1989,

STRACT

Texaco has developed a nuclear salt-in-crude monitor which continuously measures salt content of a flowing stream of crude oil. The monitor consists of two parts: a unting chamber and an instrument console. The counting chamber is a length of 24-in meter pipe containing a long-life neutron source and a gamma ray detector, both of ich are mounted in cross pipes so that there is no direct contact with the flowing crude. e gamma ray detector is electrically connected to the instrument console which is ated in a control room.The console contains necessary instrumentation to process the a, compute the salt concentration and provide a continuous printed record of the salt ncentration in pounds per thousand barrels (PTB).

MMENTS

This nuclear salt-in-crude monitor is developed for monitoring of chlorine content in all quantities with good accuracy, 10 PTB ± 2 PTB (approximately 20 ± 4 ppm orine). Sulfur content of less than 1% by weight and greater can also be monitored. e system has proven to be technically sound in the field environment. [HG]

.4. Recent developments

lford, J.E., Flaym, C., and Gilchrist, W.A.,Jr., Enhanced resolution processing of compensated neutron logs. *SPE Formation Evaluation,* June 1989.

STRACT

Compensated neutron logging (CNL) uses a two-detector system that was devel-ed to reduce borehole effects. The ratio of counting rates from the detectors provides basic tool response from which a porosity index is obtained. Each detector in this stem has a different vertical resolution because of its spacing. A new method of ocessing the counting rates has been developed to enhance the vertical resolution pabilities of the neutron porosity index by exploiting the better vertical resolution of the ar detector. Because no additional or new measurements are required, data from older lls can easily be re-evaluated.

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A new method to process the CNL counting rates is introduced in the paper. The v method has been developed to enhance the vertical resolution of the porosity index. e results for data sampled at 6-in. intervals is comparable to the 1-ft. vertical resolution density, MicroSFL's, and EPT logs. The typical vertical resolution from ratio processing approximately 2 ft. The statistical precision of the high-resolution processing is superior that of the standard ratio method. An additional parameter, alpha factor, provides ormation about borehole effects. Therefore the alpha factor can be used as a qualita-e indicator of gas when the invasion is not deep and environmental effects are not ge. [HG] rtner, Michael L., A new resolution enhancement method for neutron porosity tools. *IEEE Transctions on Nuclear Science, 36,* pp.1237-1242, 1989.

STRACT

The effectiveness of a new resolution enhancement method for compensated neu-n porosity logs is illustrated. The new method is the same as conventional ratio ocessing except that a smaller amount of depth shifting is used. Simulated log data is ed to show that this method inceases the vertical resolution by a factor of two: the tical resolution obtained with conventional processing is about 2 1/2 feet; with the new ethod the vertical resolution is approximately 1 foot. This method is compared with a solution enhancement proposed by Galford et al. *[see the paper listed immediately ove]* in which the log response is sharpened by obtaining the porosity from the near ector count rate instead of the ratio between near and far detector count rates. The w method produces similar results but is simpler to implement.

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The conventional processing consists of deriving the porosity from the ratio of the ar and far detectors count rates. The distance between these two detectors is 6 hes. The porosity data are obtained by compensating the near detector count rate to far detector count rate at a 6-in. depth shift. The anomalous reading at the bed undary is eliminated, but there is also a marked decrease in vertical rsolution. The new thod taking a 2-inch shift improved the vertical resolution considerably and at the same e removed most of the anomalous behavior that occurs if no shift is applied. This study licated that the vertical resolution of the porosity log is about 1 foot if a depth shift of 2 hes is used. [HG]

. Reviews

rr, S. A., and Worthington, P. F., Nuclear logging techniques for hydrocarbon, mineral, and geological applications, *IEEE Transactions on Nuclear Science,* 35, 794-799, 1988.

STRACT

This paper provides an overview of the role of nuclear-based logging techniques, ncipally in the petroleum industry, since this has been the driving force behind many of major technological innovations in logging. The nuclear processes which provide the ysical basis for logging tools are summarized together with information on the fluid/rock stem which these interactions provide. Log interpretation strategy is briefly traced from beginnings in the late 1920s to the present time to demonstrate the motivation behind se measurements. Finally, the future prospects for this developing technology, espelly in the area of spectroscopy, are assessed.

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This brief review of nuclear well-logging techniques serves as a very good introduc- n to the field. It is a little more up-to-date than the much more extensive review by yder and Fleming (see below), and its length is quite appropriate for reading by one o is just beginning to become acquainted with the field. The last two pages of the cle present the various nuclear well-logging techniques and their applications in grammatic form; this part of the article should continue to be valuable to a reader who comes familiar with the various techniques by reading other articles that have more tailed descriptions of the techniques and their applications. [JMW]

Well logging is the engineering science of downhole measurements of physical and emical properties of rocks and their constituent fluids. These measurements are ssified as acoustic, electromagnetic or nuclear. This article briefly reviewed the history n the first well logging for electrical resistivity to the modern spectroscopy techniques. nentioned the caliper and electrochemical self-potential log and their use in identifica- n of permeable zones and hydrocarbons in those zones. The development of the ural gamma-ray log and then the neutron logging tool has been widely used in the troleum industry for determination of hydrocarbons and porosity inferred from the drogen concentration. The contemporary nuclear logging technology can be divided natural which measures the naturally ocurring gamma radiation field, and the the ive logging tool, which employs a nuclear source associated with the detector(s). The st significant development is the spectroscopy capability. It varies from a simple rmal/epithermal neutron filter to full multichannel analysis of gamma ray spectra ob- ned with both scintillation and semiconductor detectors. The paper pointed out that ıre developments would include data interpretation techniques based on Monte Carlo delling, measurement while drilling, the improvement of vertical resolution, the wireline ochemical log, and related fields: the measurement of elemental concentrations in the nation rock/fluid, of the formation properties such as clay minerals, cation ex- change pacity, grain density and porosity, and finally the formation history. [HG] yder, D. D., and Fleming D. B., Well logging - A 25-year perspective, *Geophysics, 50*, 2504-2529, 1985.

STRACT

Developments in the field of well logging over the last 25 years are reviewed. face and borehole instrumentation have evolved significantly, taking advantage of dern digital and analog circuits. Most open-hole petroleum well logs are now recorded itally. Digital logs are also frequently acquired in cased-hole petroleum, mineral, and otechnical applications. Nuclear well-log measurements have become accepted and able. New measurements include borehole compensated density and neutron-porosity, ewall epithermal neutron-porosity, and most recently litho-density. The neutron decay , developed early in the 25-year period, has undergone a number of major improve-nts since its introduction. Probes which make spectral measurements of natural nma-ray emission, and gamma-ray emission from neutron interactions with matter have o been developed. Resistivity measurements are now made with probes which com-e three or more sensors each with different depths of investigation so that information out the borehole invasion profile can be acquired. Acoustic logging methods have ressed major developments and improvements. The compensated sonic measure-nt was introduced early in the period along with the cement bond logging method. erest in measurement of shear-wave velocity has produced new direct shear-wave asurements as well as improved acoustic probes for full-waveform acoustic logging.

Other interesting or promising methods which have been developed or improved ing the period include the borehole televiewer, the borehole gravimeter, and the clear magnetic resonance log. The digital computer provides powerful capabilities for ll-log analysis both at the well site and in the office. Analysis of complex sand-shale and bonate formations using two or more logs in a simultaneous solution of a litho-porosity del is now routine. Powerful signal processing techniques are being applied to econvolve" well logs, to enhance or synthesize images of the wellbore, and to estimate extract information from full-waveform acoustic logs.

While new or improved measurements have been introduced and log analysts now e access to powerful computers and graphic work stations, understanding of the rophysical significance of the measurements lags behind the basic hardware measure-nt and interpretation technology.

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This extensive review of developments in well logging since 1960 emphasizes the lution that has been brought about by the application of modern data-acquisition and a-processing techniques. The review includes a wide variety of physical techniques in lition to the nuclear logging techniques. [JMW]

. Books

/lie, A. W., *Nuclear Assaying of Mining Boreholes, An Introduction. Methods in Geochemistry and Geophysics, 21,* Amsterdam, Elsevier, 344 pp.

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/IT>Of the many books about well logging that have appeared during the past cade, this one is the most useful source of information on the application of nuclear ll-logging techniques to the measurement of radioactive species and non-radioactive ›ments in shallow boreholes. The first part of the book, entitled "Nuclear Physics ckground," provides a well-written and nicely illustrated introduction to the properties of mma radiation, to the nuclear properties and geochemistry of the natural gamma-ray iitters, to the detectors (including the recently developed n-type germanium detectors) d systems used for measurement of gamma rays and neutrons, and to the production gamma radiation from non-radioactive elements by neutron irradiation.

Part II of the book is entitled "Theory and Practice of Log Analysis." Following apters on the borehole environment and on calibration of probes for quantitative liometric analysis, there are individual chapters on logging (1) natural gamma radiation, scattered neutron radiation, (3) prompt gamma radiation, (4) activation gamma radion, and 5) back-scattered gamma radiation. There is also a chapter on x-ray and other gging techniques. The penultimate chapter is a review of logging techniques applied to n ores, uranium ores, and (in considerable detail) coal. The final chapter is a descripn of logging probes and the elements of a logging system. It includes descriptions of ɔ specialized probes that should prove to be of particular importance in applications of ·ll logging to environmental monitoring — the germanium-based probe and the celerator-source probe. An appendix has listings of sources of mineralogical and clear geophysical data. [JMW]